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Defining Requirements for Advanced PHM Technologies for Optimal Reliability Centered Maintenance

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Abstract—Condition Based Maintenance Plus (CBM+) can be described as optimal condition based maintenance (CBM) procedures defined by applying the principles and process of Reliability Centered Maintenance. This approach offers a rigorous and disciplined method, based on the system FMECA, to determine the least cost maintenance policy and procedures that are consistent with acceptable levels of safety and readiness, applying available prognosis and health management tools.

It is argued that the same process is the preferred method to define requirements for advanced PHM technologies based on RCM derived capability gaps, preferably accounting for synergies with concurrent continuous (maintenance) process improvement. There may be synergies in coupling this process with Continuous Process Improvement programs, such as NAVAIR's AIRSPEED.

In discussing this proposed approach, several issues are addressed. The first is the question of interdependence between incommensurable safety, affordability and readiness objectives and metrics.

The second is the problem of uncertainty in the FMECA failure modes and probabilities until the system and equipment has accumulated considerable service history, while still subject to the emergence or aggravation of failure modes by mission exposure, component deterioration, quality escapes and intentional configuration change.

In practice it may be necessary to fall back on less rigorous (semi)qualitative methods to target innovation. In any case, more adaptable PHM architectures are needed to mitigate inevitable uncertainty in requirements. .

Note: the terms equipment health management (also, more specifically, engine health management) [EHM] and prognostic health management (or prognosis and health management) [PHM] are used with little distinction in this paper, but in general PHM is restricted to methods generating estimates of remaining useful life. [1] [2] [3]

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1. INTRODUCTION

The topic of this paper was inspired by ongoing joint US Department of Defense and UK Ministry of Defense planning for trials of advanced aircraft propulsion health management systems, under the auspices of the Military Engine Reliability and Safety [MERS] initiative.

In the course of review of the Engine Health Management [EHM] action team proposals for a demonstration of an advanced EHM system, the MERS Steering Committee actioned the EHM team to define the protocol proposed for definition and selection of the functionality of the EHM system. This paper records the answer presented to the Steering Committee, and expands on the rationale behind it.

Reflecting on a paper [1] presented last year at this conference, this task was addressed in the context of the Total Life Cycle Systems Management imperative to ensure cost effective operational readiness over the life of a weapon system in the context of the relevant military sustainment process.

The US Department of Defense Acquisition Guidebook [2] states in Section 4.1.3. - Total Life Cycle Systems Management (TLCSM) in Systems Engineering: "It is fundamental to systems engineering to take a total life cycle, total systems approach to system planning, development, and implementation. Total life cycle systems management (TLCSM) is the planning for and management of the entire acquisition life cycle of a DoD system. Related to the total systems approach, DoD Directive 5000.1 [2], E1.29, makes the program manager accountable for TLCSM". (See Table 1.)

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[2] IEEEAC paper #1264, Version 2, Dated December 18, 2008
[3] NAVAIR Public Release 08-1121

Table 1. DoDD 5000.1 E1.29. Total Systems Approach[4]

The program manager shall be the single point of accountability for accomplishing program objectives for total Lifecycle systems management, including sustainment. The program manager shall apply human systems integration to optimize total system performance (hardware, software, and human), operational effectiveness, and suitability, survivability, safety, and affordability. PMs shall consider supportability, life cycle costs, performance, and schedule comparable in making program decisions. Planning for Operation and Support and the estimation of total ownership costs shall begin as early as possible. Supportability, a key component of performance, shall be considered throughout the system life cycle.

The Defense Acquisition Guidebook continues: "Because of TLCSM, the program manager should consider nearly all systems development decisions in context of the effect that decision will have on the long term operational effectiveness and logistics affordability of the system."

This paper addresses the question of EHM system definition in the context of TLCSM, as implemented through Condition Based Maintenance Plus (CBM+) incorporating Reliability Centered Maintenance (RCM) and prognostic health management (PHM). Last year's paper [1] expanded on the logic of this linkage in the context of the role of reliability databases, and this paradigm is similarly applied here in the context of EHM/PHM requirements definition.

2. TOTAL LIFE CYCLE SYSTEMS MANAGEMENT

Total Life Cycle Systems Management is defined as the "implementation, management, and oversight, by the designated Program Manager, of all activities associated with the acquisition, development, production, fielding, sustainment, and disposal of a DoD weapon or materiel system across its life cycle"[3]. Furthermore, TLCSM must consider product support and life cycle logistics in DoD acquisition strategies with enhanced sustainment as a key performance criteria. Achieving this goal is expected to yield increased reliability and a reduced logistics footprint with performance-based logistics (PBL) strategies as a key enabler.

Kratz, Fowler and Cothran [4] note performance based logistics as the preferred strategy for sustainment, with public-private partnerships employing health monitoring and prognostics to manage defense assets, providing a support infrastructure informed by real-time situational awareness based on outcomes monitored automatically by embedded instrumentation and prognostics. This perspective expands the objectives for EHM to include more than fault and degradation detection and annunciation, as true situational awareness must include records of system, subsystem and component usage to enable near real time assessment of usage relevant to, or anticipated to be salient to, total lifecycle systems management and sustainment.

Detailed and specific measures of the usage of individual assets and their subsystems and components are required – data that is fundamental to effective prognostics, and thus RCM and CBM. However, since the specific usage metrics that are most effective for this purpose cannot be fully defined a priori, the drivers for component durability and reliability must be validated and updated based on in service experience, and experience teaches that unanticipated failure modes often dominate equipment availability and maintenance cost.

Availability of such data is also evidently crucial to definition and implementation of effective performance based logistics strategies. By analogy with the interdependent development of PHM and PBL in commercial aviation, compounded by the greater variability and uncertainty of equipment usage in military operations, comprehensive and timely records of equipment exposure and usage is necessary to mitigate support partner exposure to economic and logistical risks. Otherwise, risk premiums are likely to limit PBL cost effectiveness.

This consideration defines an overarching requirement for EHM provisions, the need to capture usage data and equipment degradation & fault indications in support of the overall TLCSM imperative. However, what information is necessary will be a function of the maintenance strategy adopted, and its implementation and evolution.

The rest of this paper examines the determinants of PHM requirements in the context of the mandated Condition Based Maintenance Plus [CBM+] strategy, informed by Reliability Centered Maintenance [RCM] enabled by Prognostic Health Management [PHM].

3. CONDITION BASED MAINTENANCE PLUS

A DoD Instruction 4151.22, [5], Condition Based Maintenance Plus (CBM^+) for Materiel Management, identifies CBM+ as "the primary reliability driver in the Total Life Cycle Systems Management (TLCSM) supportability strategy of the Department of Defense" in concert with Continuous Process Improvement and Performance Driven Outcomes achieved via Performance Based Logistics.

The Defense Acquisition Guidebook [2], Section 5.2.1.2: Condition Based Maintenance Plus (CBM+) provides this definition of CBM+:

"a set of maintenance processes and capabilities derived, in

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[4] Underlining emphasis added.

large part, from real-time assessment of weapon system condition, obtained from embedded sensors and/or external tests and measurements. The goal of CBM+ is to perform as much maintenance as possible at pre-determined trigger events. A trigger event can be physical evidence of an impending failure provided either by inspection or diagnostic technology, or could be operating hours completed, elapsed calendar days or other periodically occurring situation (i.e., classical scheduled maintenance)."

Figure 1 provides an integrated view of CBM+ which emphasizes the integration of Condition Based Maintenance and Reliability Centered Maintenance, noting the application of a broad range of EHM tools applicable to CBM.

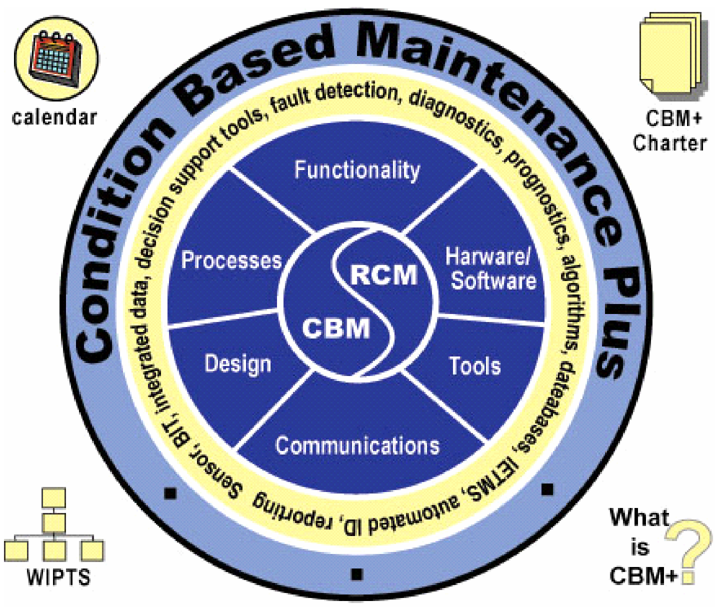

Figure 1. CBM+ Scope and Toolset (http://www.acq.osd.mil/log/mrmp/CBM+.htm, September 2007)

For our purpose, the definition of a protocol for defining EHM/PHM requirements, this coupling of CBM and RCM provided a way forward, by interpreting CBM+ as the definition and implementation of optimal condition based maintenance (CBM) informed by reliability centered maintenance (RCM).

Equipment health management (EHM) provisions, encompassing prognostic health management (PHM), can be thus seen as enablers and tools in delivering RCM defined CBM. "At its core, CBM+ is maintenance performed on evidence of need provided by Reliability Centered Maintenance (RCM) analysis and other enabling processes and technologies" [6].

4. Reliability Centered Maintenance

A web site identified with the Office of the Under Secretary of Defense (Logistics and Materiel Readiness) [7] states "RCM is a logical, structured process used to determine the optimal failure management strategies for any system, based on system reliability characteristics and the intended operating context. RCM defines what must be done to a system to achieve the desired levels of safety, reliability, environmental soundness, and operational readiness, at best cost. RCM is to be applied continuously throughout the life cycle of any system."

"As one of the key enablers of CBM+ and the life cycle sustainment of DoD weapons systems, RCM is conducted to ensure that effective maintenance processes are implemented. RCM provides a logical decision process for determining optimum maintenance approaches and establishes the evidence of need for both reactive and proactive maintenance tasks."

An instruction issued by the Commander, Naval Air Systems Command [9], emphasizes that RCM is a "continuing, integrated activity...for making affordable management decisions" as a TLCSM process, and that as such RCM influences design and development requirements, defines the preventive maintenance [PM] program for test & evaluation and sustainment, updates PM for initial deliveries and subsequent major modifications, and guides maintenance and design improvements throughout production, deployment, operations and sustainment."

"Crucially, RCM is "based on the reliability of the various components, the efficacy of maintenance actions, the severity of the consequences related to safety and mission if failure occurs, and the cost effectiveness of the task."

Figure 2, found in a Naval Air Systems Command Management Manual defining guidelines for RCM [8], and many other sources, illustrates the process of RCM definition, implementation and update. Note there are two fundamental inputs, one explicit and the other implicit.

The need for failure modes and effects criticality analyses (FMECA) for the weapon system equipment is evident, and is central to the RCM process. A critical feature is the indicated feedback from "in-service data and operator/maintainer input". This becomes another overarching requirement for EHM: data acquisition, communication and analysis to maintain a representative FMECA.

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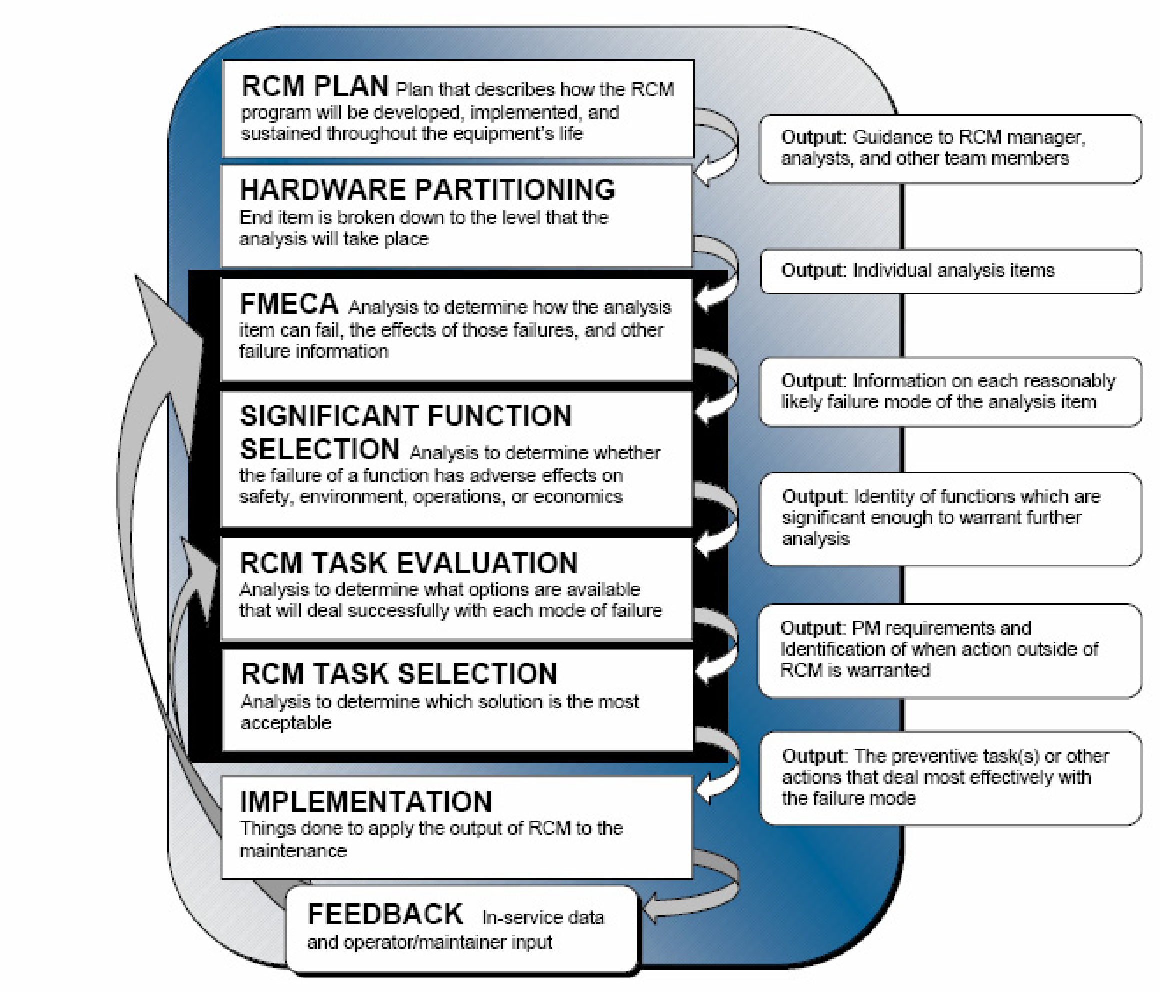

Figure 2: RCM Process Map
Extracted from NAVAIR 00-25-403 [8]

The output from the phases "RCM Task Evaluation" and "RCM Task Selection" necessitates a determination of what options are available to mitigate each significant failure mode, and which are most effective. We need to define and characterize the means at hand to deal with each failure mode, from a spectrum spanning from PHM technologies through usage driven scheduled maintenance to periodic inspection, removal, test and teardown/rebuild.

Clearly, RCM is the preferred tool to define CBM and by implication the EHM/PHM provisions enabling and supporting cost effective CBM, and the intended output of RCM included the optimal suite of CBM tools enabling an optimal maintenance process. The capabilities of individual EHM/PHM tools and any synergies (e.g., from information fusion) need to be accounted for in the RCM analysis defining optimal CBM procedures and so RCM analysis and EHM/PHM definition are interdependent. Due to the interdependence between these, an iterative systems engineering approach is recommended.

5. Prognostic Health Management (PHM)

"Prognostic health management depends on effective measures to detect degradation and impending failure well in advance of any loss of mission capability. Coupled to dependable tools to model remaining useful life, an essential PHM element, this allows delay of what would otherwise be unscheduled maintenance activity to a scheduled preventive maintenance event, or another convenient time with the least impact on equipment availability and maintenance workload." [1]

Thus, prognostic health management (PHM) is a key complement to CBM+ and RCM that also mitigates the variability in the maintenance process inherent in CBM driven by automated fault detection or periodic inspection.

RCM and PHM have evident synergies. Both require in-depth knowledge of failure modes and effects, with detail understanding of failure probability as a function of usage and state – at the individual component level. PHM adds a valuable option to the menu of available RCM tasks by mitigating the impact of failures on "safety, environment, operations and economics". (Fig. 2)

Thus, RCM analysis is our preferred and mandated tool to identify requirements for PHM systems and evaluate alternative means of meeting these. The first iteration of the systems engineering process defines a tentative optimal CBM+ strategy and maintenance process.

Given a reasonably representative FMECA and a baseline suite of proven PHM tools, a rigorous RCM analysis should yield EHM/PHM functional requirements and preferred state of the art technical approaches. If this fails to meet weapon system objectives, we may need to make tradeoffs between safety, availability, initial and recurring costs, and weapon system performance.

As the equipment and the weapon system proceed through development, qualification and operational evaluation, improved understanding of the failure modes and consequences are similarly likely to result in an updated RCM analysis and PHM requirements and implementation. As the system and equipment enters service and accumulates usage, we can anticipate further process and configuration change.

The right hand side of Figure 3 illustrates this iterative process that should yield optimal RCM while defining and validating the corresponding PHM provisions.

6. RCM + Continuous Process Improvement

The left side of Figure 3 introduces a further lesson learned from industry practices. Over the past decade productivity in manufacturing and services has increased markedly, and this is frequently attributed to continuous process improvement (CPI) that takes advantage of automation and information technology to reduce costs and improve quality.

AIRSPEED is the term used in the Navy for the deployment of these techniques. A focus of AIRSPEED is maintenance and logistics activities. The insight communicated in Figure 3 is that these are not independent activities. Both are implicated in CBM, AIRSPEED CPI can impact RCM analysis (e.g., faster turnaround and reduced costs) while a comprehensive RCM analysis may identify synergies with AIRSPEED initiatives. Both affect maintenance and logistics processes and both may drive requirements for PHM provisions. Ideally both will be conducted in conjunction and synergies will be exploited in defining PHM requirements.

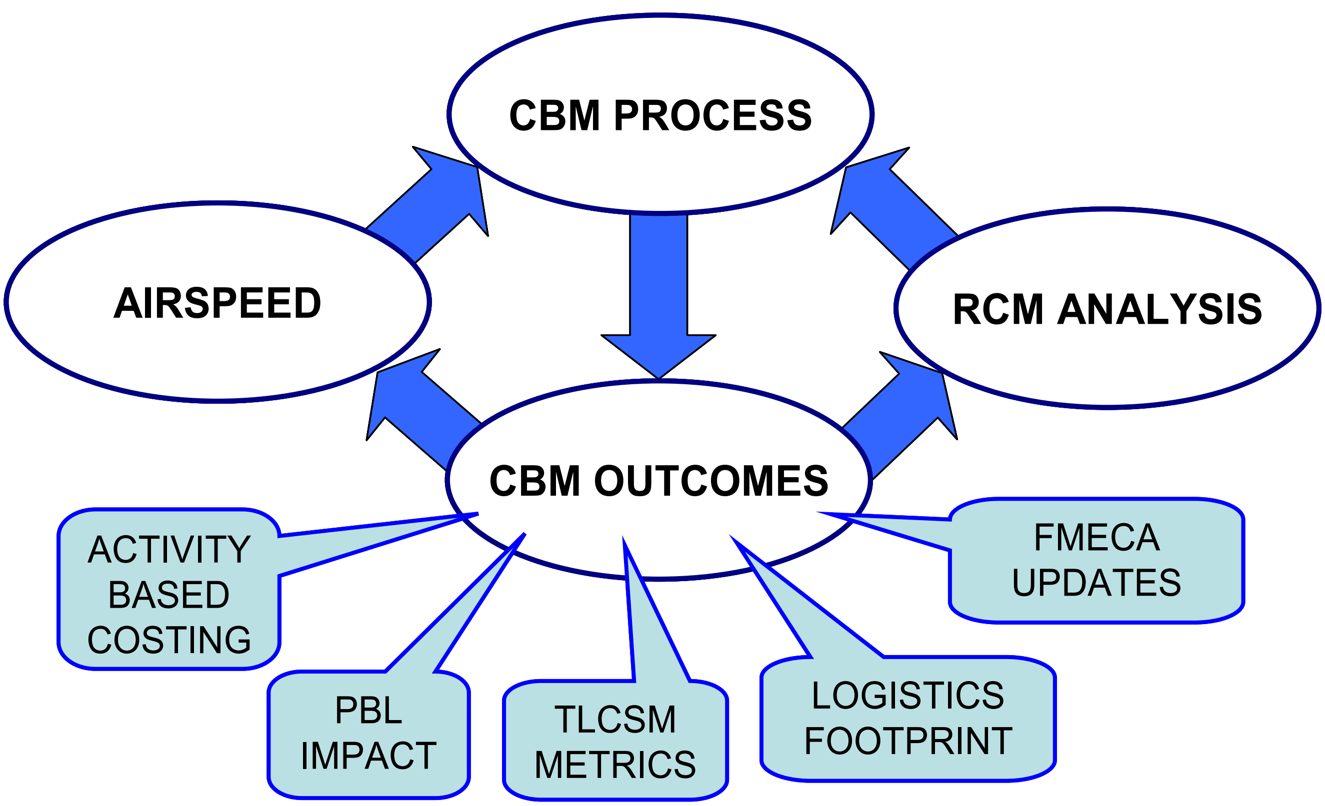

Figure 3: RCM + AIRSPEED

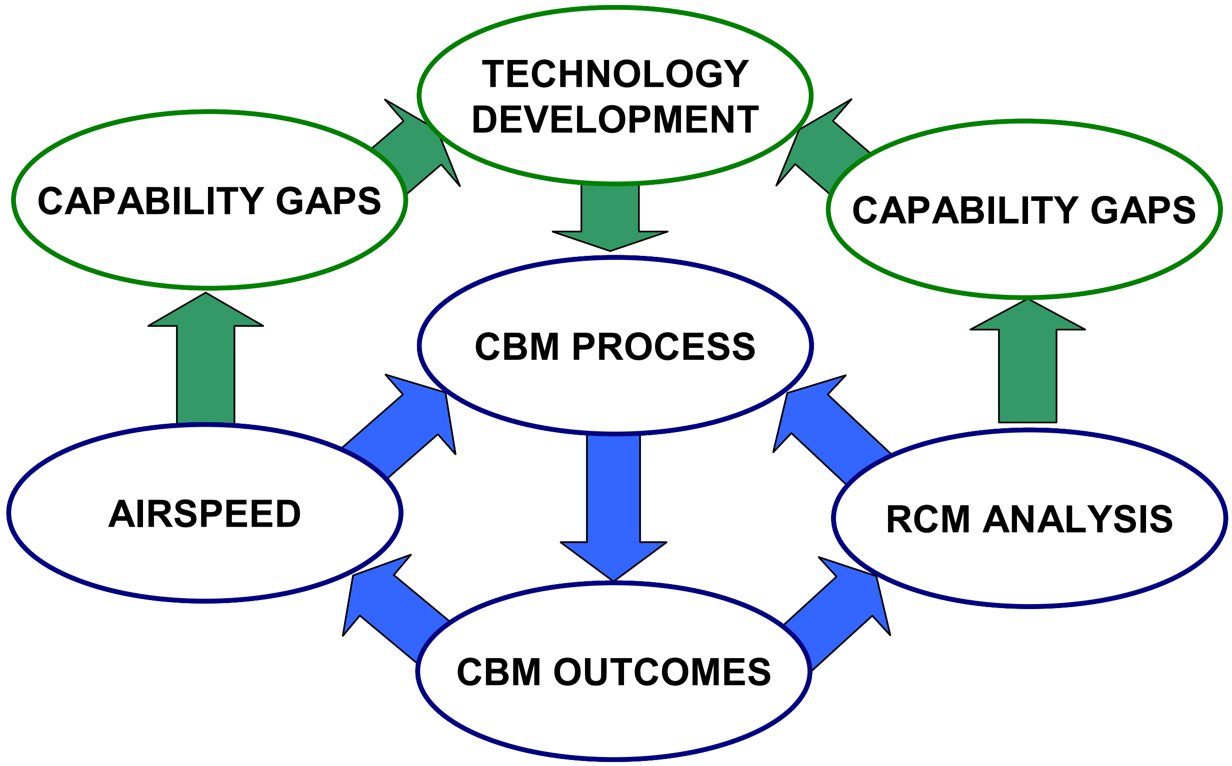

Figure 4: RCM + AIRSPEED Capability Gaps

How does this conjoined process apply to defining requirements for advanced PHM technologies? Figure 4 illustrates the identification of PHM capability gaps derived from shortcomings identified when implementing AIRSPEED and RCM analyses of maintenance and logistics processes.

Such capability gaps may justify investment in advanced PHM technology development that if successful will result in recycling through the RCM and AIRSPEED processes to define new optimal CBM based on new PHM functions. This approach appears to satisfy our search for a protocol to define and select the EHM, and thus PHM, functionality suitable for demonstration under the auspices of MERS.

In discussion of this proposal, a number of concerns have surfaced. The first is the incommensurability of the goal factors for RCM: "desired levels of safety, reliability, environmental soundness, and operational readiness, at best cost". This challenge is implicit in RCM, and all forms of systems engineering, and a variety of techniques are available to make quantitative and qualitative tradeoffs in this situation.

The formulation quoted above appears to imply that cost will be adjusted until all threshold objectives are met, but a desirable alternative is to hope that the disciplined RCM analysis will identify capability gaps to focus innovation.

A stronger objection raises the issue that in many cases the FMECA presents a spurious impression of accuracy. The source data may be scanty and analysis resources limited during design and development. Only after many years of service can a well validated FMECA be compiled from reliability databases, and by that time changes to configuration and the mission, component degradation, and quality escapes may partially invalidate this update.

There are two responses to this challenge: expert judgment and PHM system adaptability. Tools such as quality function deployment (QFD) combine limited quantitative information with expert judgment to robustly prioritize requirements. This may be the best we can do prior to development and initial operational evaluation, but we need to strive to inform these processes with the best RCM analysis possible with available data.

A more satisfactory response could be to add requirements that enhance PHM system ability to respond to the unexpected, and changes in mission and usage, rapidly at low cost. These requirements might favor "broad spectrum" PHM functionality with the potential to detect multiple failure modes and open system specifications and architectures enabling PHM system reconfiguration with minimal development and qualification cost & delay.

7. SUMMARY & CONCLUSIONS

Formal US Department of Defense documents and US Navy guidance and instructions buttress the conclusion that the preferred and appropriate basis for defining requirements for Prognostic Health Management [PHM] is a rigorous application of Reliability Centered Maintenance to define Condition Based Maintenance (CBM) provisions, including PHM, in the context of Total Life Cycle Systems Management (TLCSM). The latter and the need for a representative FMECA for RCM imply the collection and analysis of extensive usage and maintenance data.

By extension the same process should be used to define advanced PHM technology requirements. There appear to be synergies in coupling this process with Continuous Process Improvement programs, such as NAVAIR's AIRSPEED. In practice it may be necessary to fall back on less rigorous (semi)qualitative methods. In any case, more adaptable PHM architectures are needed to mitigate the inevitable uncertainty in detailed PHM requirements and functions when a weapon system first enters service.

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BIOGRAPHY

Richard Millar recently accepted a post as Associate Professor with the Naval Postgraduate School Department of Systems Engineering, based at the Patuxent River Naval Air Station. He has 35 years experience in the design and development of gas turbine engines and their integration with aircraft propulsion & power systems. He has worked in this field at General Electric, United Technologies, Rolls-Royce, Boeing, Lockheed Martin and BAE Systems prior to joining NAVAIR in 2003.

Mr. Millar acquired a B. Eng and M.Eng. (Carleton) and an MSc in Management (MIT) prior to working for the US Navy. He received a D.Sc. in Systems Engineering from The George Washington University in 2007, thanks to generous support from NAVAIR for his studies.